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The Role of Geographical Slant in Virtual Environment Navigation

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Abstract. We have investigated the role of geographical slant in simple navigation and spatial memory tasks, using a computer graphics town called "Hexatown" (Gillner & Mallot 1998). This environment was a hexagonal grid of streets with landmarks placed in each angle between two streets. The whole environment could be slanted by an angle of 4°. Three slant conditions were used: *flat*: no slant; *slanted NW*: slant direction 30° Northwest with respect to some arbitrarily chosen "North"; *slanted NE*: slant direction 30° Northeast. Twelve subjects participated in each condition. Images were projected on a 180° half cylindrical projection-screen. Subjects could interact with the virtual environment by pedaling with force-feedback on a bicycle simulator (translation) or by hitting buttons (discrete rotations in 60° steps). Subjects explored the environment by searching 15 routes to various goals presented to them as pictures. After learning, spatial memory was accessed by three tasks, using an across subjects design: (i) pointing from various positions to the learned goals (19 pointings per subject); (ii) choosing the more elevated of two landmarks from memory in a forced choice paradigm; (iii) drawing a sketch map of the environment. The number of navigation errors (wrong motion decisions with respect to the goal) was strongly reduced ($p < 0.001$) in the slanted conditions. Furthermore, subjects were able to point to currently invisible targets in virtual environments. Adding a geographical slant improves this performance. Significant differences (circular F-test) of the mean angular deviations between the "flat" and the two "slanted" conditions were found. There was also a significant difference between the two slanted conditions ($p < 0.01$). We conclude that geographical slant plays a role either in the construction of a spatial memory, or in its readout, or in both.

1 Introduction

"Navigation refers to the practice and skill of animals as well as humans in finding their way and moving from one place to another by any means. Generally moving from place to place requires knowledge of where one is starting, where the goal is, what the possible paths are, and how one is progressing during the movement" (Pick 1999).

One source of information that may be salient for navigation, i.e., for a spatial representation is geographical slant. Geographical slant is a ground that forms a natural or artificial incline, which describes an elevation gradient. In order for geographical slant to be useful for navigation, it must be on the one hand perceivable and on the other hand contain information about the goal.

First, **how well is geographical slant perceived?** Creem and Proffitt (1998) investigated the perception of geographical slant (4°, 21°, 31°) in real environments. They showed that subjects are able to accurately adjust a surface (tilt board) according to a previously seen slant with their unseen hand. In earlier experiments Proffitt et al. (1995) showed that in virtual environments, subjects are also able to reproduce accurately geographical slant (5° to 60 ° in 5 ° steps) on a tilt board. Further, the judgements in the virtual environments and the presented slants do not differ significantly.

In pilot studies (Mochnatzki 1999), we examined the perceptional thresholds for slant in our virtual environments, with three different motion models (no movement, only static viewing; predescribed velocity pattern and passive translation; translation with a force–feedback VR–bicycle). In a two alternative-force choice paradigm, the perceptual thresholds for 75 % correct discrimination of detection (uphill, downhill) were evaluated. The thresholds varied between 0.11° and 0.27° for the different motion models and slant directions (uphill or downhill). We conclude from this that subjects are sensitive to very small slants.

A further question would be, **is geographical slant used?** In the animal literature, Moghaddam et al. (1996) showed that rats are able to use slant while searching for a food source. Evidence

Figure 1: Virtual Environments Lab with 180° projection screen showing the Hexatown simulation. The subject was seated on a virtual reality bicycle in the center of the half cylinder.

for the use of slant in human spatial orientation comes from linguistic studies such as the one by Brown and Levinson (1993) on the Maya language Tzetal. This language is spoken by people living in a globally slanted environment. Terms like "uphill" or "downhill" are used as a global spatial reference system.

Our particular interest in this study is, to investigate **whether and how human subjects use geographical slant for navigation tasks?** The gradient direction of a geographical slant is a distinctive direction of an environment that might be used much like a compass and could therefore improve performance in navigation tasks. The question whether slant information in incorporated into the spatial memory acquired during exploration of our virtual environments, we measured navigation performance, quality of pointing judgements and relative height judgments. In addition, we recorded sketch map drawings.

2 Method

2.1 Subjects

A total of 36 subjects (18 male and 18 female, aged 15–31) took part in the experiment. Participation in this experiment was voluntarily and a honorarium was paid for participation.

2.2 Virtual Environment

2.2.1 Graphical Apparatus.

The experiment was performed on a high end graphics computer (Silicon Graphics Inc. ONYX2 3–pipe Infinite Reality), running a C–Performer application that we designed and programmed. The simulation was displayed non–stereoscopically, with an update rate of 36 Hz, on a half–cylindrical projection screen (7m diameter and 3.15m height, Fig. 1). The computer rendered three 1280 × 1024 pixel color–images projected side by side with a small overlap. Images were corrected for the curved surface by the projectors to form a 3500 × 1000 pixel display. For an observer seated in the center of the cylinder (eye height 1.25m), this display covered a field of view of 180° horizontally times 50° vertically. The field of view of the observer was identical to the field of view used for the image calculations. A detailed description of the setup can be found in Veen et al. (1998).

2.2.2 Scenery.

In this experiment, we used three identical environments varying only in geographical slant (Fig. 2). In the control condition, the environment was on a flat plane (*Flat*). In the two other conditions, the environment had a global geographical slant with a slant angle of 4°. (The slant angle is the angle between the surface normal and the vertical; a slant angle of 4° is equivalent to an inclination of 7%.) These environments differed in the orientation of the slant with respect to an arbitrarily chosen "North" direction. In one condition, the geographical slant was oriented in the direction of Northeast (*NE*). In a further condition, the slant was to the Northwest (*NW*).

The model of the environment was generated using MultiGen 3–D modeling software. The environment consisted of an octagonal ground plane surrounded by a flat background showing a regular mountain range. The buildings were constructed using Medit 3–D modeling software. A schematic map of the town is shown on the right site in Fig. 2. This aerial view was never shown to the subjects. The virtual environment (called "Hexatown", see Gillner and Mallot, 1998, Steck & Mallot 2000, and Mallot & Gillner 2000) consisted of a hexagonal raster of streets with a distance of 100 meters between adjacent junctions. A junction was built of three adjoining streets forming 120° corners. In each corner, an object (building, gas station, etc.) was placed, see Fig. 2. At the periphery of Hexatown, streets ended blindly. These dead–ends were marked by barriers 50 meters from the junction. A circular hedge or row of trees was placed around each junction with an opening for each of the three streets (or dead ends) connected to that junction. This hedge looked the same for all junctions and prevented subjects from seeing the objects at distant junctions.

The usage of geometrical cues, as demonstrated, e.g., by Hermer and Spelke (1994), is not possi-

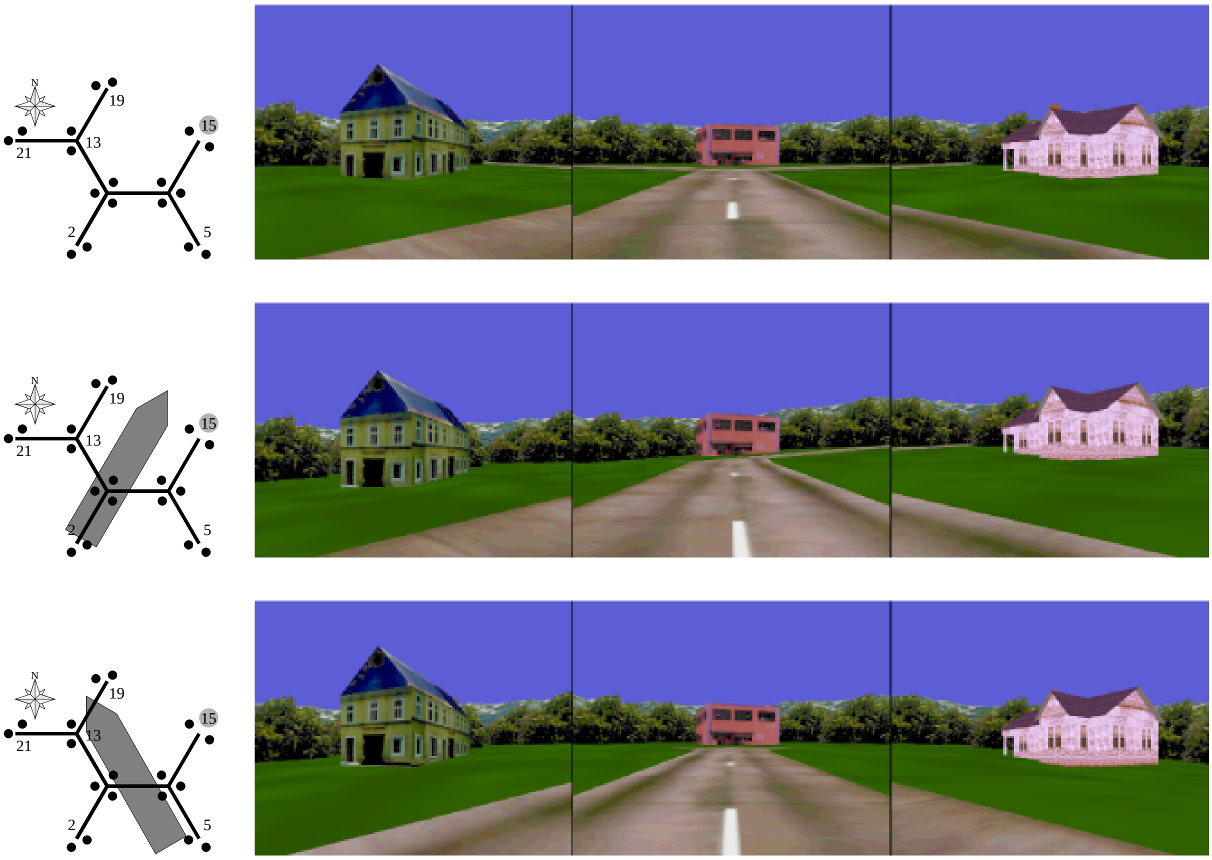


Figure 2: Overview over all three conditions. **Left:** map of the environments. Landmarks indicated by numbers have been used as goals in the exploration phase and as targets in the pointing phase. **Right:** subjects perspective. Each row shows the three pictures projected on the 180° screen. The images are projected with a small overlap, resulting in the apparent discontinuities in these figures. The picture shows the view from the place with object 5 in the direction of the street towards the only adjacent place. **Top row** shows the *Flat* slant condition. **Middle row** shows the *Northeast* slant condition. **Bottom row** shows *Northwest*.

ble in Hexatown. All junctions are identical and symmetrical, so that when approaching a junction, one cannot infer the approach direction nor the approached place from the geometrical layout. Rectangular city rasters are also symmetrical, but have the disadvantage that the straight–on direction is preferred. The type of symmetrical junctions we used were triangular Y–junctions with the streets forming 120° angles.

2.2.3 Interaction.

Subjects navigated through Hexatown using a virtual reality bicycle (a modified versions of a training bicycle from *CyberGear*^{TM}, s. Fig. 1, for extra information Veen et al. 1998). This device provided not only visual, but also proprioceptive information to the subjects.

At the junctions, 60° turns could be performed by pressing the left or right button on the bicycle. The simulated turn movement was "ballistic", with the following predefined velocity profile: turns took 4 seconds, with a maximum speed of 30° per second and symmetric acceleration and deceleration. The smooth profiles for rotation were chosen to minimize simulator sickness. Translations on the street were started with a button press. The velocity was dependent on the pedal revolution and the geographical slant, according to a physical motion model. Since the subjects could only influence the speed, but were not able to change the direction, they were restricted to the streets.

In the sequel, the motion initiated by pressing the buttons will be referred to as motion decision.

2.3 Procedure

Subjects were run through the experiment individually. The experiment had four different phases: a navigation phase, pointing judgments, elevation comparison, and map drawing. In the navigation task, the subjects had to find a previously shown goal using the shortest possible path. The navigation phase consisted of 15 search tasks. In the pointing judgment, subjects were asked to carry out directional judgements to previously learned goals. In the elevation judgements, subjects had to choose which learned goal was higher up in the environment. This part was omitted in the *Flat* condition. Finally, subjects had to draw a map from the learned environment. For each part, subjects were instructed separately. Therefore, they were uninformed of all tasks in advance. On average, subjects needed 90 min for all tasks.

2.3.1 Navigation Phase.

First, the subjects had to solve 15 search tasks in the primarily unknown environment. In the beginning, subjects started at landmark 15 (Fig 2). Before each trial, a full 180° panoramic–view at the goal location was shown. By pressing a button on the handles of the VR–bicycle, the goal presentation was terminated and subjects were positioned at the current starting position. When they had reached their goal, a message was displayed, indicating whether they had used the path with the least number of motion decisions ("fastest" path), or not. The task was repeated until completion without mistakes. During the entire navigation phase, the subjects had the possibility to expose a small picture of the current goal object on a gray background in the bottom left corner of the middle screen by pressing a special button. The starting point of the first five tasks was landmark 15 (*home*). Since, after these five routes the whole street net of Hexatown was visited, those routes were called *exploration*. The next ten routes were either *return paths* from the previously learned goals to the landmark 15, or *novel paths* between the goals, which were learned in the exploration phase. The navigation phase ensured that all subjects reached a common fixed performance level for the subsequent pointing judgments.

2.3.2 Pointing Judgments.

Pointing judgments were made to evaluate the internal representation of the learned environment. The subjects were placed in front of a learned goal, which was randomly chosen. They were asked to orient themselves towards one of four other goals (except *home*) by continuously turning the simulated environment. A fixed pointer superimposed on the turning image was used to mark the forward direction to which the goal had to be aligned. Alltogether, the subjects had to point to twenty goals. One of these goals was directly visible from one of the reference points. This pointing task was therefore excluded from further analysis.

2.3.3 Elevation Judgments.

In order to test whether elevation information was also stored, elevation judgments were collected in the *Northeast* and *Northwest* conditions. Two goals of different elevation were presented in isolation on a gray screen and the subjects had to decide as accurately and as quickly as possible, which goal had appeared at higher elevation in the training environment. For each of the two

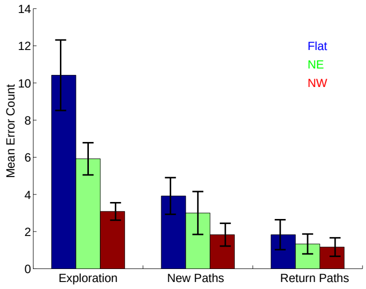


Figure 3: Mean error count in the navigation phase. Mean number of errors separated by the three different path types (*exploration*, *return paths*, and *novel paths*). Dark bars for the *Flat* slant condition, light gray for the *NE* condition and dark gray for the *NW* condition. The error bars present one standard error of the mean.

slant conditions, ten pairs of goals were selected and tested.

2.3.4 Map drawing.

In the final phase of the experiment, subjects were asked to draw by hand as detailed a map of the test environment as possible. They were given a pen and a paper. The paper had a printed frame to restrict their drawings. There was no time limit for the subjects.

3 Results

3.1 Errors in the Navigation Phase.

In the navigation phase, the trajectories of the subjects for every search task were recorded. Every movement decision that did not reduce the distance to the goal was counted as an error. Figure 3 shows the mean number of errors per path type (*exploration*, *return paths*, and *novel paths*) and per slant condition. A three–way ANOVA (3 path types × 3 slant conditions × gender) shows a significant main effect of slant condition ($F(2, 30) = 5.78$, $p = 0.008$**). As figure 3 shows, more errors were made in the *Flat* condition than in the *Northeast* condition. In the *Northwest* slant condition, the least amount of error was made. Further, there was a highly significant main effect of the path type ($F(2, 60) = 27.69$, $p < 0.001$***). In all three slant conditions, the most errors were made in the *exploration* (first five paths, all starting from home). The second greatest number of errors were made for the *novel paths* (connection paths between goals, none of which was the home 15). Although the *return paths* alternated with the *novel paths*, the number of errors made for the *return paths* was the smallest. On average, the *return paths* were longer than the *novel paths*.

Comparison	F(198,198) $= \frac{mad_1^2}{mad_2^2}$	p
F– NE	1.72	< 0.001 ***
F – NW	3.5257	< 0.001 ***
NE – NW	2.0408	< 0.001 ***

Table 1: Comparison of the variances of the slant conditions (*Flat*: F, *Northeast*: NE, *Northwest*: NW.

Further, the interaction between slant condition and path type was significant ($F(4, 60) = 4.37$, $p = 0.004$**). Since the number of errors for the *Northwest* slant condition was very small in the exploration, there seems to be a "floor effect" compared to the other slant conditions. No difference in the mean number of errors was found between men and women (men: 11.5 ± 1.9, women: 10.2 ± 1.6, $F(1, 30) = 0.300$, $p = 0.59$ n.s).

3.2 Pointing Judgments.

The values of pointing judgments were stored as degree values according to the arbitrarily chosen North. Since pointing judgments are periodic data (e.g., 181° is the same direction as −179°), we used circular statistics (see Batschelet 1981) to analyze pointing judgments. The circular means ($\bar{\alpha}$) were calculated by summing the unit vectors in the direction of the angles. The resultant vector was normalized with the number of averaged vectors. The length of the mean vector is a measure for the variability of the data.

To compare the different slant conditions, the deviations from the correct values were averaged over all tasks. Figure 4 shows the deviation from the correct values for all tasks and all subjects. The measured values were distributed in 9° bins. The arrow shows the direction of the circular mean of the errors. The length of the mean vectors is inversely proportional to the "mean angular deviation" shown as circular arcs in Fig. 4. Although the means do not differ significantly, the mean angular deviations (*mad*) do differ significantly, s. Tab. 1. For comparing the variances of the different slant conditions, we compared the arithmetic mean of the squares of the mean angular deviation of each subject[1] using the circular F-test (Batschelet 1981, chap.6.9). There is a highly significant difference between all conditions, see table 1.

[1]For small angles is $\frac{1}{n}\sum_{i=1}^{n}(\epsilon_i - \bar{\epsilon})^2 \approx 2(1 - r)$, ϵ_i measured values, and r vector length of the mean vector.

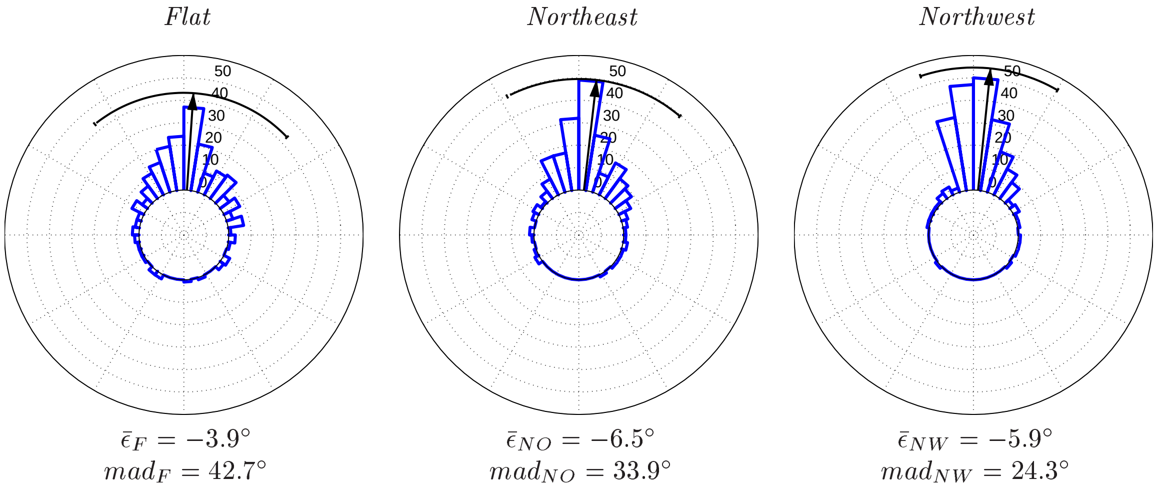


Figure 4: Pointing Error. Circular plots for the slant condition Flat, Northeast and Northwest. $\bar{\epsilon}$: circular mean of the error (arrow). *mad*: mean angular deviation (segment).

3.3 Elevation Judgment.

In this part, subjects in the slanted conditions were tested to determine, if they stored the relative elevations of the objects. The subjects in the *Northwest* slant condition gave 109 correct answers out of 120, 90.8%, and the subjects in *Northeast* 94 correct answers out of 120, 78.3%. The answers of the subjects differed significantly from a binomial distribution with $p = 50\%$ which would imply pure guesing. ($\chi^2_{NE}(10) = 492.0$, $p < 0.001$***, $\chi^2_{NW}(10) = 3838.9$, $p < 0.001$***). Therefore, we conclude that the subjects were able to differentiate object elevation. The percentage correct of the *Northwest* condition was significantly higher than the percentage *Northeast* (U-Test after Mann and Whitney $U(12, 12, p = 0.05) = 37, p \leq 0.05$*).

3.4 Map drawings.

The map drawings were used to study how subjects implemented the geographical slant in their representation. Single maps were mostly quite good, since the geometry of the junction was often correctly depicted. Only three out of thirty–six subjects drew all junctions as right angle junctions. Four further subjects drew right angles at some junctions. All except one very sparse map (*vkl*), contained object 15, which was the start point of the first five routes. Object 15 was a sign with the Max-Planck-Institute (MPI) logo.

We were interested in whether the slant conditions influenced the map drawings. Therefore, all maps were examined for alignment. A map was considered "aligned", if either a uniform orientation of lettering (e.g., Fig. 5 top right) or a perspective of the drawn objects (e.g., Fig. 5 top left) was apparent to the authors. The maps were categorized in four groups: NE–up, SE–up, SW–up and NW–up. Table 2 shows schematic examples for the different alignment categories and also lists the number of drawn maps for all alignment categories for the three different slant conditions (*Flat*, *Northeast*, and *Northwest*). In the *Flat* slant condition, the SW–up alignment was found six times. In this alignment category, object 15 is at the lower edge of the map, and the street, which leads to the next junction, points to the top. Further, the category NE–up (in which the object 15 is at the top edge of the map, and the street, which leads to the next junction, points to the bottom) occured three times. In the *Northeast* slant condition, the alignment category NE–up occurred six times and SW–up two times. In both cases (NE–up, SW–up), the maps were aligned with the gradient along the geographical slant, with the majority of the maps aligned to the uphill gradient. In the *Northwest* slant condition, the alignment category NW–up (i.e., uphill along the gradient) occurred five times. There were two maps of the category NE–up and one map of the category SW–up. The distributions of the maps in the alignment categories differ significantly ($\chi^2(NW/F) = 30.5$, $df = 3$, $p < 0.001$***, $\chi^2(NW/NE) = 14.0$, $df = 3$, $p = 0.003$**, $\chi^2(NE/F) = 9.5$, $df = 3$, $p = 0.02$*). The alignments of the *Northeast* slant condition were similar to the alignments of the *Flat* slant condition, since the object 15 is on the top of the slant.

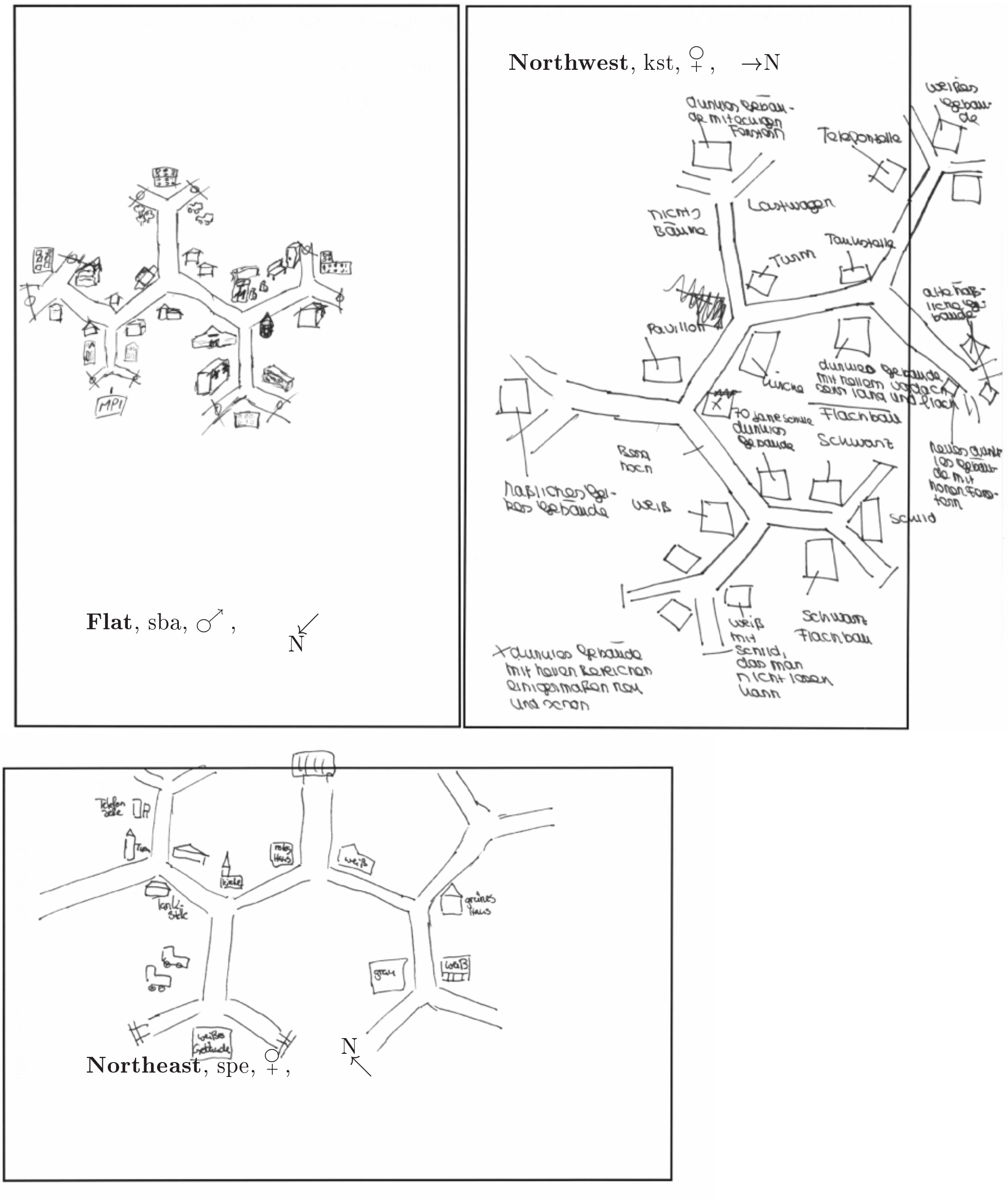


Figure 5: Examples for aligned maps. The top left map (*sba* in *flat*) shows an alignment (perspectivic drawing) from bottom to top, Southeast is on the top of the drawing. The top right map (*kst* in *Northwest*) has an alignment (letters) along the gradient of the slant towards Northwest. The bottom map (*spe* in *Northeast*) has alignment along the gradient towards *Northeast*. That is to say, both maps from the slanted environments are aligned such that uphill is at the top of the drawing. The boxes are the frames printed on the sketching paper to prevent subjects from starting their drawings to closely to the edge of the paper.

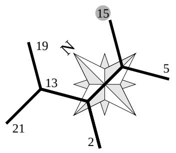
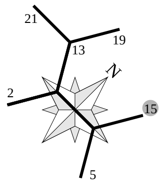
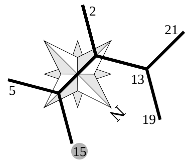
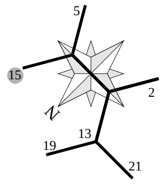
Alignment	NE–up	NW–up	SW–up	SE–up	could not be categorized
					
Flat	3	0	6	0	3
Northeast	6	0	2	0	4
Northwest	2	5	1	0	4

Table 2: Overview over the map categories, subdivided over the alignments of the maps. Maps were drawn from the subjects (from left to right) arranged according to the slant conditions (from top to bottom).

4 Discussion

Two main conclusions can be drawn from this experiment:

1. **Geographical slant improves pointing judgements.** In the conditions with geographical slant, the pointing judgements were significantly better. The variability of the pointing judgments of the subjects who had geographical slant information was less than the variability of the pointings in the *Flat* slant condition. The global slant can be used as a compass or a global frame of reference. This global frame of reference can be used to integrate the spatial relationships between the non–visible objects by the subjects.

   We found no difference in judgment accuracy between pointings parallel to the slant and pointings perpendicular to the slant. However, there was also a significant difference between the variability of the *Northwest* and *Northeast* slant conditions. One explanation for the better performance in *Northwest* slant condition could be the relative orientation between the streets and the geographical slant. In the *Northwest* condition, there was a four–segment street with a zigzag pattern along the geographical slant from 5 to 19. It could be possible to associate these street segments as a main street, from which only one–segment streets branch. In the *Northeast* condition lead the streets like a fork along the geographical slant from 2 to 15 and 21. The unequivocal slant information could be easier to use, since it is possible to define an unique uphill-downhill relation. In contrast, in the *Northeast* condition the goal objects 15 and 19 , as well as 21 and 5 have the identical elevation.

   From the pointing judgment, it cannot be inferred whether the geographical slant was embedded in the structure of the spatial representation, since the test was performed in the same environment as the training. While pointing, the subjects could also perceive the geographical slant. However, results of the elevation judgements and the map drawings suggest that slant information is incorporated in spatial memory.

2. **Global slant is used as reference system.** The subjects performed very well for the relative elevation judgments (84.6% correct answers). Gärling et al. (1990) found similar results for relative elevation judgments in a city (76.5% correct answers). Furthermore, most maps in the slant condition showed an alignment effect (which was given either through lettering or the perspective of drawn objects) with the geographical slant. Almost half of all maps were aligned with the uphill slant.

Comparison of the results with other experiments. To compare our results with other studies that did not use circular statistics, we calculated mean absolute error for the pointing judgments. The mean absolute error averaged over all conditions is 41.8°, and for the best condition was (*Northwest*) 27.0°. Chance et al. 1998 tested different motion models and compared the accuracy of the pointing judgments. The tested environments were not visible from one vantage point, the size of the maze was 3m by 5m. The subjects judged the directions relative to a "virtual guide" in minutes on an imagined clock face (i.e., 60 "minutes" are 360°). In three sessions, the subjects had to point to learned objects from different positions. In the last session in the condition, where the subjects could only move with the joystick, the mean error was about 70°. For the "real walk" condition, where the subjects actually had to walk, the mean absolute error was a little bit below 50°. Our pointing results seem to be comparable, if not more accurate than the pointing results of Chance et al. (1998), although the subjects in our experiment had only visual and proprioceptive (VR-bike) information. In comparison, the subjects in Chance et al. "real walk" condition had additional vestibular information available. In the following studies, it is not clear how the direction estimates have been calculated from the raw data. One can assume that the given "mean direction estimates" are the mean absolute errors. Ruddle et al. (1997) replicated a study by Thorndyke and Hayes–Roth (1982). Subjects had to learn the position of rooms in a building. Subsequently they had to make pointing judgments. The environment was about 100m by 50m. In VE-replication, the mean absolute error was about 30°. The "real" study error was about 20°. These mean absolute errors are slightly more accurate than those found in our study. However, our environment (300m by 260m) was larger than the environment of Thorndyke and Hayes-Roth (1982).

In summary, we conclude from this study that geographical slant improves pointing judgments. And further, geographical slant is incorporated in the human spatial representation of the environment.

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